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SUBLIMATING COMETS AS THE SOURCE OF NUCLEATION SEEDS FOR GRAIN CONDENSATION IN THE GAS OUTFLOW FROM AGB STARS

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ABSTRACT. A growing amount of observational and theoretical evidence suggests that most main sequence stars are surrounded by disks of cometary material. In this paper we investigate the dust production by comets in such disks when the central stars evolve up the red giant and asymptotic giant branch (AGB). Once released, the dust will be ablated and accelerated by the gas outflow and the fragments will become the seeds necessary for condensation of the gas. The origin of the requisite seeds has presented a well known problem for classical nucleation theory. This model is consistent with the dust production observed in M giants and supergiants (which have increasing luminosities) and the fact that earlier supergiants and most WR stars (whose luminosities are unchanging) do not have significant dust clouds even though they have significant stellar winds. Another consequence of the model is that the spatial distribution of the dust will not in general coincide with that of the gas outflow, in contrast to the conventional condensation model. A further prediction is that the condensation radius is greater than that predicted by conventional theory, in agreement with IR interferometry measurements of α-Ori.

I. INTRODUCTION

The sources of the small dust grains observed by IRAS around Vega, β-Pic and numerous other old main sequence stars (Aumann, 1985; Backman and Gillett, 1987; Walker and Wolstencroft, 1988) are believed to be disks of cometary material (Harper et al., 1984; Weissman, 1984; Matese et al., 1987). Modeling of the IR emission yields dust disk radii extending to several hundred AU (Gillett, 1986). The disk in β-Pic has been resolved optically and it extends to $\approx$1000 AU (Smith and Terrile, 1987). The mass of the small ($\sim$10μm) grains directly observed is $> 0.01M_{\oplus}$ (e.g. Gillett, 1986). However, the lifetime of these small grains is less than the probable ages of the stars (Whitmire et al., 1988) and therefore more massive unobserved sources must also be present. Estimates of the total disk masses are highly uncertain since it must be assumed that a standard mass distribution index holds over a range from the observed small grains up to an assumed maximum mass. If

the maximum mass is taken to be comet size, total mass estimates range from $\sim$10-300$M_\oplus$(Harper et al., 1984; Weisman, 1984; Gillett, 1986). Taking into account observational bias, it is likely that most main sequence stars (including the sun) possess disks of cool orbiting grains (Aumann, 1985; Backman and Gillett, 1987), implying that the phenomenon is not indicative of young systems as originally conjectured. Further, several F-type stars with 60μm excesses have age estimates of $\approx 2 \times 10^9$ yr (Backman and Gillett, 1987).

These observations are consistent with the theoretical expectation (Kuiper, 1951; Cameron, 1962) that a primordial disk of residual unaccreted planetesimals should exist just beyond the planetary region of the Solar System. This disk has previously been invoked as the source of the observed steady state short period comets (Fernandez, 1980; Matese and Whitmire, 1986a,b) whose flux (Fernandez, 1980) and inclinations (Duncan et al., 1988) are inconsistent with their origin as captured long period comets. In addition to this residual flattened planetesimal disk there is also theoretical evidence suggesting the existence of an isotropic massive ($\sim$100 $M_\oplus$) inner Oort cloud extending inward to just outside the planetary region (Hills, 1981; Weissman, 1985; Bailey, 1983). However, since the dust clouds around β-Pic and α-Psa are known to be flattened we assume that it is the residual planetesimal disk that dominates within several hundred AU of the star.

In this paper we investigate the dust production by disk comets around intermediate mass stars ($\approx$1-10$M_\odot$) as they evolve into red giants and especially red supergiants (AGB phase). During the AGB phase the stellar luminosity can increase to 10^4-$10^5 L_\odot$, depending on mass. We will argue that if a modest population of comets ($\sim$1$M_\oplus$) exists within 100 AU of these stars they can readily supply the seeds ($\gtrsim 10$ Å) necessary for dust condensation in the gas outflow, thereby mitigating the classical nucleation problem of statistically producing sufficient critical clusters in this environment (Donn and Nuth, 1985; Draine, 1985).

II. ANALYSIS

Iben and Renzini (1983) have modeled the evolution of intermediate mass stars in the AGB phase. The time dependence of the stellar luminosity can be written as

$$L(t) = L(0) \exp(t/\tau_L) \tag{1}$$

where

$$L(0) = 26.5(M_i/M\ )^{2.68} L_\odot \tag{2}$$

and

$$\tau_L = 6.5 \times 10^7 (M_i/M\ )^{-3.64} \mathrm{yr}. \tag{3}$$

In these formulae $t = 0$ at the beginning of the AGB phase, and M_i is the initial zero-age main sequence stellar mass. These formulae are applicable for masses in the range $1M_\odot \leq M_i \leq 10M_\odot$, however for masses $< 2M_\odot$, M_i should be set $= 2M_\odot$. The stellar luminosity, radial distance R and black body temperature T are related by

$$L(t) = (R/AU)^2(T(t)/280K)^4 L_\odot \qquad (4)$$

while the time-dependent black body temperature can be written $T(t) = T(0)\exp(t/\tau_T)$ where the temperature time scale $\tau_T = 4\tau_L$.

Since, in a standard cometary mass distribution, most of the mass resides in the largest bodies, we consider comets of a single mass $M_{max} \equiv 10^{21}$ g. The total mass loss rate for observed comets can be fit to the form (Ney, 1982)

$$dM/dt = -kM^{2/3}\exp(-1552K/T) \qquad (5)$$

where the Boltzmann factor is appropriate for the activation energy of water released from clathrates and the coefficient k depends on specific surface absorptivity and activity, being smaller for older comets like Encke. This semiempirical formula is applicable for black body temperatures T up to ≈700K, which encompasses the temperatures of relevance in the present analysis.

Equation (5) can be integrated to give

$$E_1\left(\frac{1552K}{T}\right) - E_1\left(\frac{1552K}{T(0)}\right) = \frac{640\ yr}{\tau_L}\left(1 - f^{1/3}\right) \qquad (6)$$

where E_1 is the Error function, $f \equiv M/M_{max}$ = fraction of original mass surviving. The numerical factor was evaluated by taking $k = 3.7 \times 10^{-4}\ g^{1/3}/s$ (comet Encke). We shall assume that the second term is negligible compared to the first, an adequate approximation after several luminosity timescales have elapsed. Eq. (6) gives the value of T when M has been reduced to fM_{max}.

We now locate that position in the disk where sublimation is maximal. Setting $\ddot{M} = 0$ we find

$$\frac{\exp(-1552K/T_p)}{1552K/T_p} = \frac{640\ yr}{\tau_L}\frac{f_p^{1/3}}{2} \qquad (7)$$

where T_p is the black body temperature where the comet is undergoing peak sublimation and f_p is the surviving mass fraction at peak sublimation. T_p is also a rough lower limit to the black body temperature at the inner edge where $f = 0$. An adequate approximate solution to this equation is found to be

$$T_p \approx 1860K/\ln(\tau_L/400\ yr). \tag{8}$$

Having obtained the temperature at which comets are undergoing peak sublimation rates we next determine the disk location R_p where this occurs and take this as an adequate (upper bound) approximation to the inner edge. R_p is found from

$$R_p(t) \approx (L(t)/L_\odot)^{1/2}/(T_p/280K)^2 AU \tag{9}$$

or

$$R_p(t)/R_*(t) = \tfrac{1}{2}(T_*/T_p)^2 \tag{10}$$

where * refers to stellar parameters. In Table 1 T_p, f_p and R_p/R_* are tabulated for several stellar masses. R_p/R_* is given for two stellar temperatures corresponding to α -Ori (oxygen supergiant) and IRC 10216 (carbon supergiant).

Table 1

			R_p/R_*	
$M_i/M_\odot$	T_p(K)	f_p	T_*=3300K	T_*=2300K
2	194	0.33	145	70
4	270	0.34	75	36
6	341	0.35	47	23
8	423	0.36	30	15
10	509	0.37	21	10

Finally, if one approximates that sublimation occurs only at the location of the peak sublimation

$$dM_{net}/dt \approx (dM/dR)\ (dR/dt)|_{R_p(t)} = (2\tau_L)^{-1}(RdM/dR)|_{R_p(t)} \tag{11}.$$

For any standard radial power law $RdM/dR \approx \Delta M(\tfrac{1}{2}R \rightarrow 2R)$ in order of magnitude. Therefore, if there is $\sim 1M_\oplus$ of comets available we should be releasing it at a rate

$$dM_{net}/dt \sim \Delta M/\tau_L \sim \begin{cases} 10^{-7} M_\oplus/yr \text{ for } M_i = 2M_\odot \\ 10^{-4} M_\oplus/yr \text{ for } M_i = 10M_\odot \end{cases} \tag{12}$$

To order of magnitude this result is of general applicability and can also be used, for example, to estimate the dust production rate around red giants as well as red supergiants.

III. DISCUSSION

Although these dust production rates are incapable by themselves of explaining the observed dust clouds around most M giants and supergiants they can readily supply the seeds (> 10Å) necessary for dust condensation in the gas outflows. Seeds of radii ~10Å which subsequently grow to ~0.1μm represent a dust mass enhancement factor of ~10^6. The required seeds should be readily produced by ablation in the dense gas outflow, sputtering, grain-grain collisions, or they could simply correspond to the lower end of a standard mass distribution of the sublimating particles. The seeds will simultaneously be accelerated until there is little relative velocity between the seeds and the gas outflow, at which point condensation may occur rapidly. We note that the temperature T_p in Table 1 is the black body temperature at the location of those comets which are undergoing peak sublimation, but the temperature of the small condensing grains ($\lesssim$ 0.1μm) that are actually observed can be significantly higher (e.g. 1000K).

The inner radius of the best studied oxygen supergiant α-Ori has been resolved with IR interferometry and found to be ≈ 35 - 60 R_* (Bloemhof, 1984; Howell et al., 1981), consistent with the proposed model but much larger than expected by conventional condensation theory (Draine, 1985). In other cases it is often assumed that T = 1000K which implies an inner edge ≈5R_* for black body radiators (Tielens, 1988).

The proposed model is consistent with the fact that M giants and supergiants have significant dust clouds while earlier supergiants and most WR stars do not, even though they have significant mass loss via stellar winds. It is only the cool giants and supergiants that have rapidly increasing luminosities, and therefore short time scales τ_L, as they evolve. Most of the comets within a few hundred AU should be concentrated in a disk. Thus, we expect the sublimated seeds and condensed dust to be preferentially concentrated near the disk. Dust disks are compatible with the observed asymmetries in the IR emission in IRC 10216 and other cool giants (e.g. Zuckerman, 1980; Beckwith, 1985). A prediction of the model is that the spatial distribution of the dust will not in general coincide with that of the gas outflow, in contrast to conventional condensation theory. Although R_p is uncertain by a factor of ≈ 2, the model predicts that the inner disk edges will tend to be further out than suggested by conventional condensation theory, especially for the lower mass stars.

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